POSITION ESTIMATION FOR THE PMAC MOTOR IN AUTOMOTIVE DRIVE APPLICATIONS.

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The permanent magnet AC motor requires absolute position information to be supplied to the controller so that the applied winding currents can be modulated in synchronism with the rotor. The design of controllers which can operate without position feedback have been the subject of intense development. The most commonly cited justifications for the elimination of the absolute position encoder are those of cost, and also reduction of the physical dimensions of the motor. The position estimation technique to be developed must be robust to external torque disturbances and preferably robust to electrical parameter variations over time. Certain military specifications apply stringent restraints to the use and application of sensors and estimation techniques. Absolute position encoders are in this case prohibited due to the relatively fragile nature of the glass index disk found in the encoder. The same restriction applies to manufacturers' specifications concerning electric vehicle traction drives. Fully sensorless operation has been the focus of development for all classes of electric motors, in particular the PMAC. Unfortunately the use of state observers is viewed by industry with suspicion in terms of the computational effort required and also the question of robustness, speed of convergence and low speed operation. A solution is presented which satisfies the constraints of physical and computational robustness, and is experimentally verified.

1 Introduction

The states available for estimation of the PMAC motor are the direct and quadrature currents, rotor velocity and rotor position. The estimation of rotor motion has been the focus of intense study. The methods range from waveform detection methods developed for switched reluctance motors [1] which identify events such as peaks or zero crossings in the motor electrical waveforms. However, performance is limited since not all the information contained in the electrical waveforms is utilised. Extracting all the information contained in the waveforms is achieved by modelling the motor dynamics driven by the same inputs as the motor, and to design a controller to minimise the errors between the model and the motor. In this case the model accurately reflects the behaviour of the real motor. The simplest approach to sensorless PMAC operation requires the estimation of the position of the flux linkage vector [2]. It was found with this method that operation was possible down to a low frequency limit of $1.0Hz$. Below that frequency, the stator voltage is dominated by the stator resistance drop, and the switching noise generated by the three phase inverter. In this case, an open loop starting algorithm was designed to accelerate the rotor up to the critical frequency. This approach is further developed [3] by combining the flux position estimator with a two degrees of freedom H^{∞} velocity controller. The argument is presented that extended Kalman filter and state observer algorithms present too great a computational load for real time control applications. However in the intervening five years both DSPs and PCs have entered the processing region of greater than $20Gflops$ and thus this argument no longer holds true. The constraint of initial conditions is important [4]. In permanent magnet machines, the initial value of flux linkage is defined by the position of the rotor. Therefore to evaluate accurately the initial condition necessary for the integral to calculate flux linkage, it is suggested that the rotor is somehow bought to a known position which defines the initial values of the integration. Variable inductance can be applied as a method of position detection [5]. The rate of change of current is a function of electrical position, this scheme has been applied to stepping motors and switched reluctance motors by measuring the phase currents and voltages [6] ,[7], and then using a position-current-inductance lookup table to estimate position. It has also been suggested that impedance [8] offers more accurate results with PM sinusoidal machines since there exists a problem separating the effects of resistive, reactive and motional components. This method doesn't apply in this case, since sufficient variation in inductance over an electrical cycle does not exist in the surface mounted PMAC motor. The flux linkage estimation method performance suffers due to the integration method by which the flux linkage is obtained. These techniques suffer from the effects of integrator drift which must be compensated for either by analogue electronics or software algorithm in addition to the initial condition problem previously outlined. In observer based systems, states can be accessed which are not directly measurable. The systems described thus far use the open loop flux linkage estimated value as the control parameter. In an observer based system this quantity is used to estimate a measurable quantity and thus update the motor model and compensate for effects such as compensator drift. Observer techniques based upon measuring input and output parameters to generate a corrected model [9] has been investigated. This method estimates the flux linkage as described earlier in this text, except that it uses the estimated flux linkage value together with measured current to estimate the phase voltage. The error between measured and estimated voltage is used to correct the flux linkage estimate. In [10] the predictor corrector method is further developed. A nonlinear reduced order observer can also be designed to fulfill the task of position estimation. Consider a nonlinear system given by

$$\frac{dx}{dt} = f(x) + g(x)u \tag{1}$$

$$y = hx \tag{2}$$

a non linear observer can be designed [11],[12] so that the observer equation is given by

$$\frac{d\hat{x}}{dt} = f(\hat{x}) + g(\hat{x})\,u + G(\hat{x}, u, y)\,[y - h(\hat{x})] \tag{3}$$

The gain matrix $G(\hat{x}, u, y)$ is a non linear function of the estimated states and measured inputs and outputs, being designed so the error dynamics are asymptotically stable. If the state vector x is partially known, then only the unknown states need to be estimated. A reduced order observer can be designed with a lower dimension than a full order observer. Since stator phase currents and voltages can be directly measured, a second order observer can be designed. This type of reduced order observer based on least squares optimisation and a bilinear representation of the back emf function has been proposed [13]. Since the observer is unable to produce estimates at low velocity, again an open loop scheme is introduced for startup and direction reversal. The open loop controller is a constant amplitude variable frequency excitation with extra functions built in to achieve transition between closed and open loop mode. It is noted that in general the open loop controllers suffer from well known shortcomings; it is inefficient for light loads, it will fail for large commanded accelerations, may produce torque ripple and may result in momentary direction reversal at startup [14]. Accurate instantaneous knowledge of rotor position is necessary for ripple free commutation of the motor. A typical minimum resolution [15] of 5^o electrical is frequently quoted for sinusoidal commutation. This constraint is easily achieved via an absolute position encoder typically giving 12 to 16 bits of positional accuracy. This option is not available in our case due to constraints in terms of physical robustness and also the desire to limit the physical dimensions of the motor. In the literature review it has been shown that by the use of various combinations of input and output measurements, an observer can be constructed which estimates the position of the rotor, and contains various elements of prediction and correction to increase the robustness of the estimator.

2 PMAC Commutation

Since specifications do not allow the fitting of an absolute or incremental position encoder or sole reliance on position estimation, a novel method must be devised. Commutation of the machine is possible by fitting the mechanical commutation mechanism from the equivalent brushless DC machine The device comprises a rigid shutter plate attached to the rotor shaft which switches optical hall effect sensors mounted on the motor casing backplate. The mechanical device is physically robust to standards acceptable in both military and traction applications. The device can also be mounted inside an existing motor casing with only minor modifications. The criteria of minimising the physical dimensions of the motor is not compromised. Also, no open loop low frequency algorithm is required. The drawback associated with the proposed method is that of exaggerated levels of torque ripple. The torque ripple produced by the PMAC motor is a function of the correlation [16] between the shapes of the applied and back emf waveforms. If the machine is assumed to have a fundamental sinusoidal emf with minimal harmonics, then the machine will produce an extremely even torque output when commutated with sinusoidal currents. The experimental machine was simulated with both an absolute position encoder and a dc hall effect encoder (giving a maximum resolution of 30^o electrical). In all the simulations in this section, the motor is simulated as being uncoupled to the load motor/gearbox combination, and is accelerated from rest under a demand for maximum torque. Current control is performed by a dynamic model reference controller [17],[18]. Comparison is made of the feedback signals from the absolute and dc encoders together with the subsequent torque output from the motor. The stepped hall effect signals occur in figure 1 due to rotor motion opening or closing the optical hall effect sensors. The rotor position is represented by the encoder as a three bit word. The output of the absolute position encoder is represented by the smooth line, which the hall effect encoder accurately matches at only six discrete points

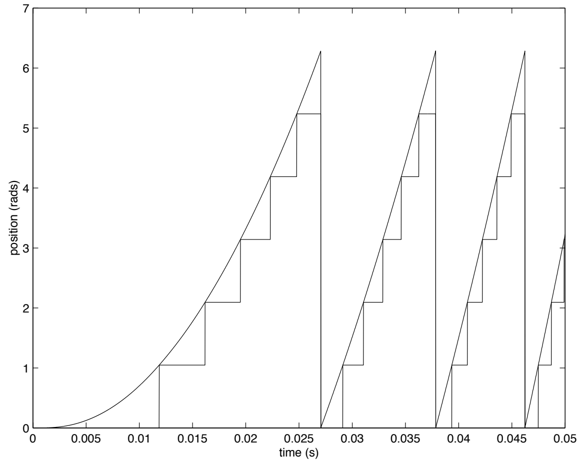

Figure 1: Simulated absolute encoder versus hall effect encoder feedback signals

every electrical cycle. The effect of this positional error is shown in the torque profiles from the simulation shown in figure2. The motor with the hall effect en-

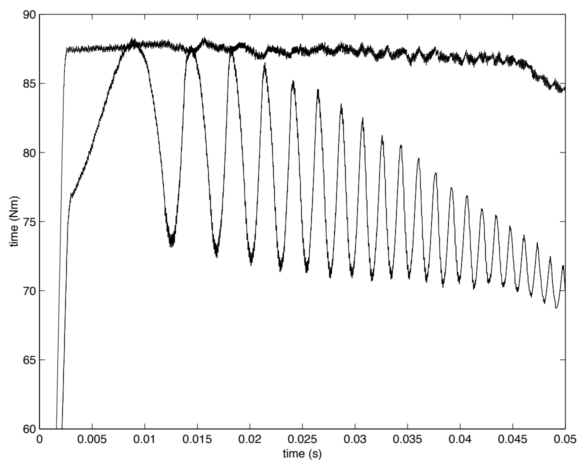

Figure 2: Simulated torque profiles of motor with absolute encoder and Hall effect encoder

coder as simulated in figure 2 produces an unacceptable level of torque ripple, especially considering that one of the main advantages of the PMAC is the inherently low level of torque ripple when sinusoidally commutated. The performance of the PMAC with dc commutation can be radically improved by using the previous hall encoder information to predict the rotor position between encoder events. The position θ can be expressed as a polynomial function

$$\theta = At^2 + Bt + C \tag{4}$$

Where A,B and C are polynomials of the quadratic function. If the coefficients can be expressed in terms of present and historical position information, then prediction of rotor position is possible. If the evaluated coefficients are substituted into the original equation, then an expression is found which predicts the position from three known rotor positions. This quadratic prediction is only accurate under constant velocity or acceleration. The quadratic estimation was implemented as a simulation. The torque en-

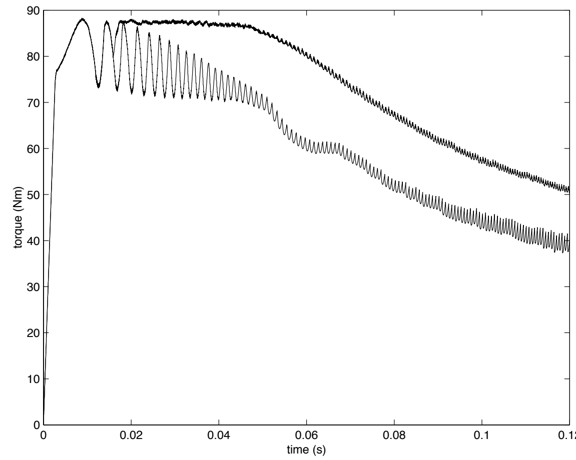

Figure 3: Torque profile comparison for PMAC fitted with Hall effect encoder, with and without quadratic estimation

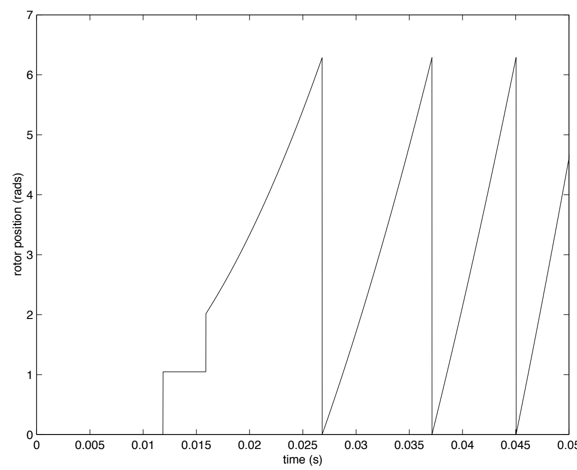

Figure 4: Position signal from hall effect encoder supplemented with quadratic position estimation

velope for the quadratic scheme in figure 3 exhibits both reduced ripple and enhanced levels of torque output compared to the basic encoder. The controller has been designed using a technique which satisfies the constraints of physical robustness and dimensions. Even in the presence of failure of any estimation techniques, the motor can be commutated albeit with increased levels of torque ripple. The commutation of the motor at startup and during change of direction is implicitly taken into account by the closed loop controller and requires no external open loop controller. The problem now concerns the estimation of position between hall effect events during disturbances and also the smoothing of the ripple in the torque profile at startup.

3 Estimation scheme extension

It is proposed to supplement the operation of the dc encoder with quadratic estimator with a nonlinear observer to reduce the torque ripple during external torque disturbances. As previously discussed, the stator phase currents and voltages are easily measured and consequently the reduced order observer becomes a second order dynamic system of the form

$$\left| \begin{array}{c} \frac{d\hat{\theta}}{dt} \\ \frac{d\hat{\omega}}{dt} \end{array} \right| = \left| \begin{array}{c} \hat{\omega} \\ \hat{a} \end{array} \right| + G\left(\hat{\theta}, \hat{\omega}\right)(y - \hat{y}) \qquad (5)$$

The performance of the quadratic estimator can be improved at startup by utilising a first order approximation to supply the position estimation until enough hall events have occured to provide a reliable estimate by the quadratic estimator. The reduced order estimation scheme is then implemented to run in parallel with the quadratic estimator. The quadratic scheme will produce position errors during changes in the external load torque or inertia. This effect is of particular importance during gearchange operations in vehicle drive applications. It has been a requirement of this implementation that the control schemes should be compatible with a two speed automotive gearbox without synchromesh capabilities or clutch. This means that in order to achieve gearchange, the velocities of the input and output shafts must be matched to within 5%. In order to achieve smooth gear disengagement, torque must be controlled to zero, which relies on accurate position estimation to produce ripple free output. The supplementary position estimation scheme allows the time constant of the gearchange process to be as short as possible, and with the lowest level of vibration due to torque ripple. The algorithm is extremely simple in application, and is a three rule administration. When the motor starts from rest, the position estimation is a first order approximation. As soon as sufficient samples are available, the estimation switches to a quadratic form. If the position estimated by the two schemes diverges, the state estimated position is utilised until the next hall event (which is an accurate update of position). The state estimated position is used until the quadratic estimation agrees with the actual position at a hall event, at which time the output from the quadratic estimator is readopted.

4 Experimental results

The position estimation schemes were implemented experimentally with a hall effect encoder fitted to the PMAC machine in tandem with a 12 bit absolute encoder which provides a reference with which to compare the performance of the estimation schemes. In

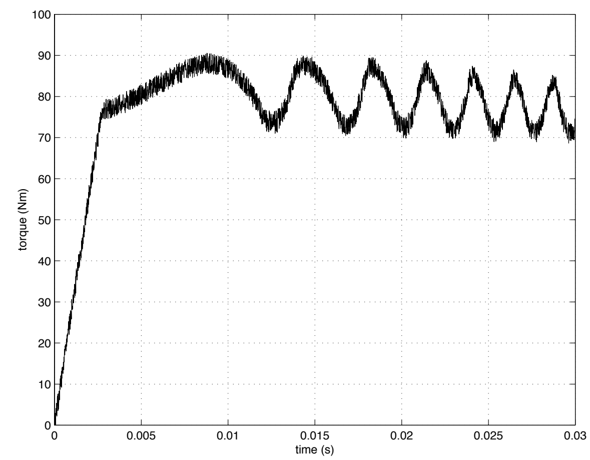

Figure 5: Experimental torque profile with Hall effect encoder

all cases current control was provided by the model reference dynamic controller previously developed. Feedback of position is provided by the dc encoder and the motor accelerated from rest with a maximum torque demand. As predicted by the simulations, the torque profile exhibits large amounts of torque ripple. The current controller is trying to synthesise sinusoidal current from a six step position encoder, and consequently synthesises three phase six step current waveforms. This six step synthesisation is reflected in the torque ripple in figure 5 which represents the base line performance achievable with this technique. If all subsequent estimation schemes fail, the machine can be succesfully commutated by the dc encoder alone albeit with consequent torque ripple. This commutation can be implemented in hardware as a safeguard should the microprocessor control fail. The quadratic extrapolation scheme when implemented produces a drastic improvement in the torque profile in figure 6. After sufficient hall events have occured to estimate position with the quadratic algorithm, the torque profile smooths out to match that expected from an absolute position encoder. The algorithm is extremely economical in terms of computation, and robust to military specification should the estimation scheme fail. The reduced order observer was implemented in parallel with the quadratic estimator to provide position estimation during external torque or inertial disturbances. At startup shown in figure 7, a first order approximation is utilised until sufficient events have occured to allow estimation by the quadratic estimator resulting in a vastly enhanced torque profile at startup shown in figure 8 when compared to the torque profile using the dc encoder alone. The final experimental implemen-

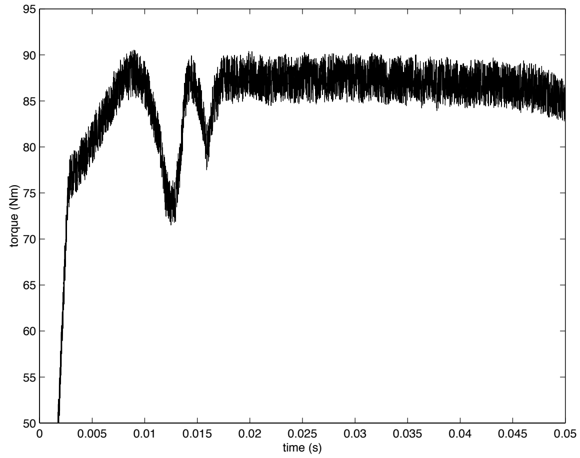

Figure 6: Experimental torque profile with dc encoder and quadratic position estimation

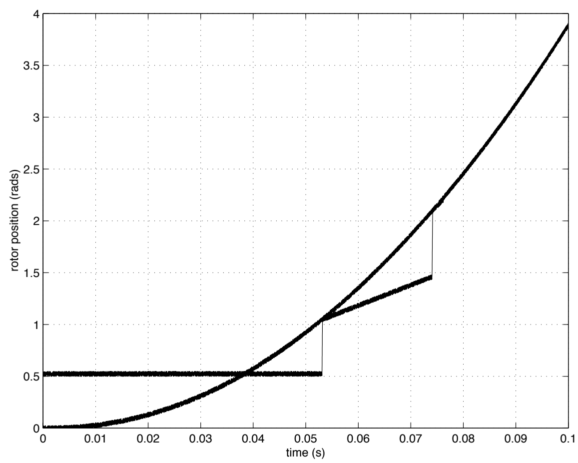

Figure 7: Estimated position compared with actual position at startup. First order and quadratic estimator, experimental results

tation is the addition of the state estimation backup algorithm to make the quadratic estimator robust to torque and inertial disturbance. As stated earlier, the output of the observer is utilised whenever it diverges from the output of the quadratic estimator. In the position estimation results shown in figure 9, the estimated rotor position is superimposed on the output of the absolute encoder which represents the waveform of accurate position. The motor is accelerated under maximum torque demand to a rotor velocity of $50 rads/s$ driving the load motor via an electromechanical clutch and two speed gearbox. The clutch is disengaged, and the rotor allowed to carry on accelerating. This represents the severest type of duty the position estimation algorithm is likely to experience during the prescribed gearchanging operation. The estimation algorithm accurately tracks the real position even during a particularly severe external disturbance.

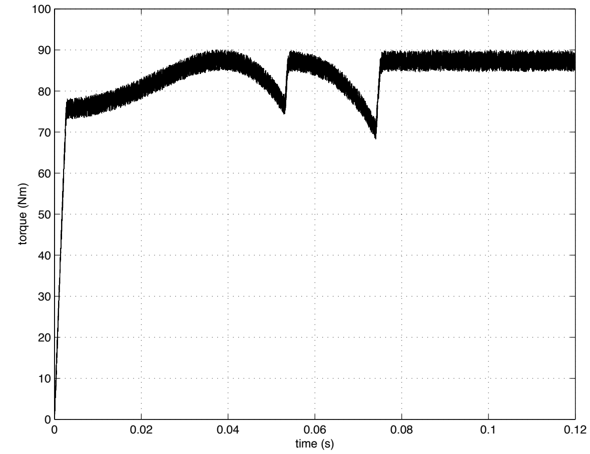

Figure 8: Torque profile at startup, first order and quadratic position estimator

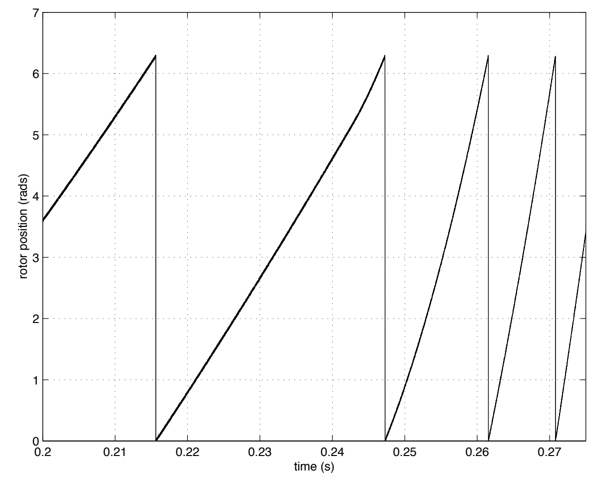

Figure 9: Actual and estimated position with large external inertial disturbance at approximately 50 rads/s (0.2475 seconds), with full estimation scheme

5 conclusion

A method of commutating the PMAC motor has been presented which satisfies several strict caveats. The commutation can be carried out without recourse to the relatively fragile external absolute position encoder. The physical dimensions of the motor can remain relatively untouched by building a dc hall effect sensor type encoder into the motor casing. This has the dual advantage of physical robustness and small size. Primary position feedback is performed by an extremely robust quadratic estimator, which is acceptable for military and traction applications. The quadratic estimator is extended in the background by a nonlinear reduced order observer which it complements during periods of external disturbances. The technique has been experimentally validated, and has proved itself appropriate for use with the specified low mass clutchless gearbox.

6 Motor parameters

The algorithms proposed were implemented on an experimental test rig with motor parameters: $L_s = 1mH$; $R = 22m\Omega$; $k_e = 0.23V/rad/S$; $t_e = 0.44Nm/A$; $J_{rotor} = 0.017s$; $J_{load} = 0.41s$; $V_s = 87V$; $I_{max} = 200$.

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